LM Glasfiber

# Improved lightning protection system enhances the reliability of multi-MW blades

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## Abstract

Lightning strikes are the worst enemy of wind turbine blades. The powerful energy discharge during lightning strikes can cause severe damage to blades, at worst leading to complete failure. Offshore wind turbines are the most exposed, as the blades are the highest point for miles around. They are thus more likely to attract lightning strikes than turbines built on land, where there are other tall objects, such as trees and antenna masts.

Offshore wind farms make demands on service and maintenance that are different from demands on similar farms on land. Access to offshore wind turbines is more difficult, and in rough weather, they may be completely inaccessible for several days. Even in calmer weather, operation and maintenance are more demanding at sea. The operation and maintenance of offshore wind farms have turned out to be between five and ten times more expensive than wind farms on land. The MW size of the offshore turbines also makes increased demands on their reliability, as breakdowns result in expensive loss of production.

Effective lightning protection is therefore crucially important. And the use of carbon fibre in large-size blades means the challenges will become even greater.

LM Glasfiber continues to develop even more effective lightning protection of LM blades. The latest measure is the use of segmented diverter strips for the protection of carbon fibre blades in particular. LM DiverterStrip was developed in conjunction with what is currently the longest blade in the world – the LM 61.5 P – as an integrated part of the development project.

Unlike systems used elsewhere for the protection of carbon fibre blades, LM DiverterStrip is mounted on the surface of the blade. This prevents lightning from damaging the blade's surface – an advantage when compared with using metal mesh or a conductive coating. LM DiverterStrip creates a channel of ionised air above the diverter and thus effectively conduct the lightning away to the lightning receptor mounted on the blade, and designed to receive the full force of the lightning current.

## Lightning

Lightning events consist of a series of consecutive stages that need to be analysed when developing lightning protection systems: (1) an initial corona forms, (2) streamers develop out of this initial corona, (3) leaders subsequently grow and (4) a final jump occurs, culminating in the development of a highly conductive channel, visible as the lightning flashover.

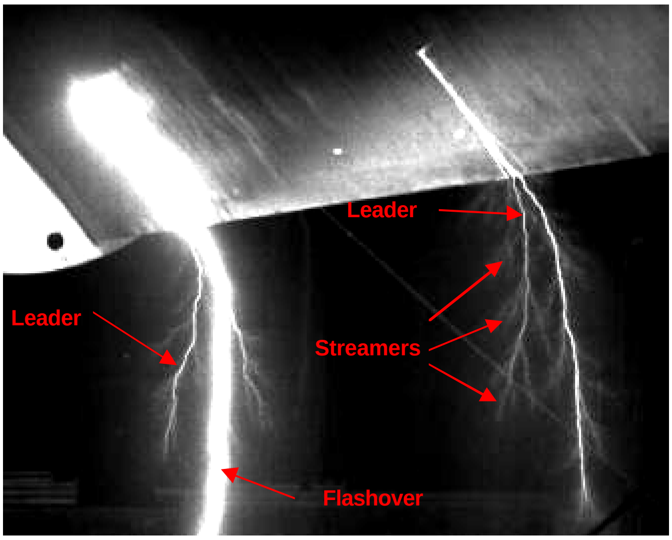



**Figure 1:** The different stages of a lightning event photographed during a laboratory test on LM DiverterStrip.

The strength of the lightning strike can vary considerably and is usually recorded as a value measured in amperes in the actual lightning strike (flashover). The general view that the more extensive the lightning (ampere value), the more dangerous it is for the wind turbine (and for that matter, for people) is not entirely correct. It is perfectly true that once lightning has struck an object, the damage caused by major strikes is more extensive than that caused by less powerful strikes. However, there is a greater risk of being struck by lightning of minor current. There are two reasons for this. Firstly, minor lightning strikes occur more often and secondly, they hit lower objects more frequently, partly because the step length of the leader is shorter in less powerful lightning strikes.

"Normal lightning" usually has a maximum stroke of approximately 30 kA. Although major strikes feature more than 150 kA, they only account for approximately 0.5% of all naturally occurring lightning strikes. [1]

### Lightning strikes hitting wind turbines

Statistics show that lightning causes 4–8 faults per 100 turbine years in northern Europe and up to 14 faults in southern Germany. 7–10% of all lightning events involve the blades of the wind turbine, and these are the components that are most expensive to repair. These statistics extend over a nine-year period from 1990 to 1998, and mostly relate to blades not fitted with lightning protection. [2]

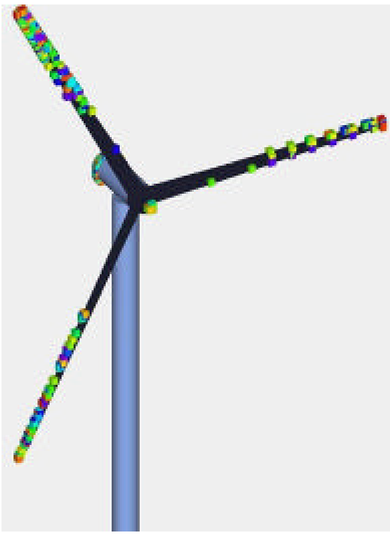
Using the approved RSPHERE [3] numerical code program for predicting lightning attachment, based on the rolling sphere concept, it is possible to predict which part of the turbine will be struck by lightning, depending on the strength of the lightning strike (measured in amperes).

The general expectation has always been that lightning would normally strike the terminal at the tip of the blade. Sometimes, however, the strikes puncture the blade inboard of the tip, penetrate it, and are then intercepted by the conductor inside. This often results in a badly damaged blade, requiring expensive repair or replacement, and thus downtime for the wind turbine installation as a whole.

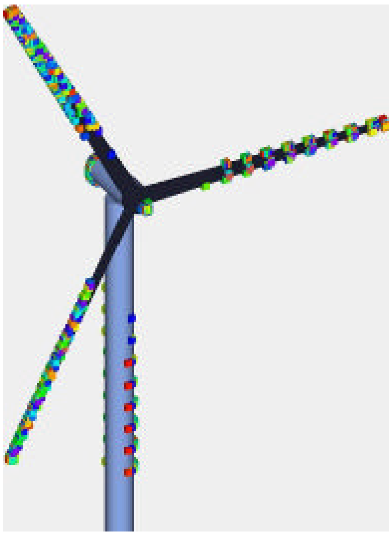
It is possible to imagine lightning strikes occasionally hitting the side of a blade when one blade is positioned horizontally, as shown in figure 1, because a leader approaching the horizontal blade intensifies the electrical field on the side as well as at the tip. RSPHERE simulation with the rotor in this position therefore represents the worst case for lightning strikes on rotor blades.

**Figure 2:** (A, B, C) RSPHERE simulation with 30,653 strikes on a turbine equipped with 60 metre blades, total height 180 metres.

A: Lightning attachment points for the 2000 most powerful strikes < 100 kA



B: Lightning attachment points for the highest 2000 strikes < 50kA



C: Lightning attachment points for the highest 2000 strikes < 20kA

The colour code in figure 2 is based on a standard spectrum that changes from blue to green to red, where blue is the lowest strike amplitude value and red is the highest in a given range. The maximum stroke current was set to 100 kA and the minimum was set to 5 kA. 100 kA was chosen as the maximum current because strokes above 100 kA will only strike the tip ends of all three blades.

This picture shows that powerful lightning (illustrated in red) tends to strike the tip most frequently, while less powerful strikes hit further down the blade (illustrated as blue and green areas). The tower is also hit using the calculation 2,000 strikes <20 kA, for example.

This therefore results in 90% of lightning strikes in the range 5–100 kA hitting the rotor, compared with only 7% hitting the nacelle. The tower is only affected by lightning strikes <40 kA.

Mounting a lightning protection system in the blade tip provides good results. However, to achieve a very high level of protection, this must be mounted well down the blade towards the root end. This is particularly important for carbon fibre blades and blades mounted on offshore wind turbines.

## Lightning protection of carbon fibre blades

Protection of carbon fibre blades involves a different, more complex set of challenges than protecting blades made exclusively of glass fibre since carbon fibres as opposed to glass fibres are conductive.

These challenges are briefly outlined as follows:

A. Faulty strikes

Damage to glass fibre blades most frequently occurs on the leading and trailing edges. However, damage to unprotected carbon fibre blades occurs in the load-bearing main laminate, because this is where the conductive carbon is located. The findings of LM Glasfiber high-voltage impact tests carried out on prototype carbon fibre blades show that although carbon fibre is traditionally a semiconductive material – and resistance is thus many times greater than for metal – it is struck by lightning just as frequently as the actual lightning receptors. The leader and streamer propagation occurs at the same speed from both materials. The challenge is thus to ensure rapid streamer and leader propagation from those places on the blade where lightning strikes are intended to take place. At the same time, streamer and leader formation should be prevented from those places where lightning strikes are least desirable, such as carbon fibre laminate, which for practical reasons cannot be designed to withstand the effects of the lightning stroke current. Even a medium-strength lightning strike that directly hits the carbon fibre main laminate will result in extensive damage.

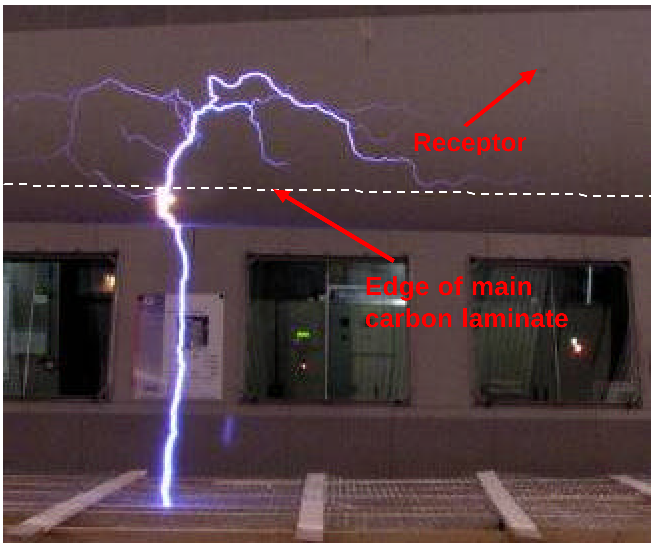



**Figure 3:** High-voltage impact test. The leading edge of the main carbon laminate is more likely to attract the lightning than the receptor seen in the upper right corner – no diverters mounted.

B. Internal flashover

A combination of carbon fibre and metal conductors requires particular care regarding electrical voltage potential. If such care is not taken, the transfer of an electrical spark can occur between the conductive parts when the lightning current is distributed down through the blade at high frequency. This is because the inductance coefficient is different in carbon fibre and metal, the two conductive materials present. Over time, the formation of large sparks inside the blades results in damage, because it can lead to carbonisation. This in turn gives rise to new electrically conductive connections. Subsequent lightning strikes affecting these carbonised areas will be disastrous, with the most serious resulting in the blade bursting into flames.

C. Current distribution

The high-current tests carried out by LM Glasfiber have shown that it is not sufficient to use carbon fibre laminate alone to conduct the lightning current down through the blade. Carbon fibre laminate is incapable of absorbing the specific energy from a level 1 lightning strike (current = 200 kA, specific energy = 10 MJ/ohm ) without resultant damage. It is also extremely difficult to distribute the lightning energy in a carbon fibre laminate without resulting in burning and subsequent deterioration of the carbon fibre laminate's strengths.

**Figure 4:** Provoked high-current impact to the edge of the main carbon laminate, in compliance with the IEC 61312 annex C standard, 217 kA, 3.28MJ/ohm. The result is a large hole in the main laminate, sufficient to cause the blade to collapse in a real-world situation.

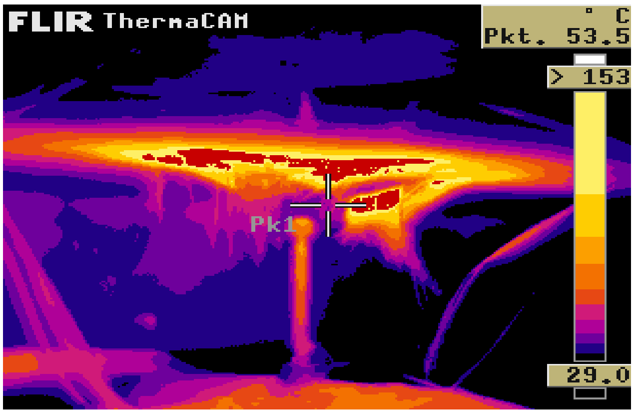



**Figure 5:** The same event as shown in figure 13, but photographed with an infrared camera 10–15 seconds after impact. The temperature scale shows that parts around the hole are more than 153°C, and the fibres in the middle of the hole are still on fire.

## Background for LM DiverterStrip

In the early development stage of the LM 61.5 P – the largest wind turbine blade in the world, constructed with a carbon fibre main laminate – LM Glasfiber focused on designing a low-maintenance lightning protection system. This meant that the familiar methods for protecting carbon fibre were not suitable for the purpose. A frequently used method is casting a metal mesh placed in contact with the carbon fibre laminate beneath the blade's painted surface. However, lightning strikes that reach this mesh result in surface damage that must be inspected and repaired.

An entirely new concept needed to be developed and integrated into the blade construction – consisting of a combination of new and already familiar lightning protection methods. Lightning protection was thus an integrated part of the development work carried out on LM 61.5 P carbon fibre blades, right from the very beginning.

One challenge was to increase the receptors' ability to capture the lightning strikes and thereby avoid faulty strikes to the semi conductive carbon fibre as shown in figure 3. In this regard, LM Glasfiber was inspired by the diverter strips used in aviation. Diverter strips have been used for a number of years to protect the radar dome mounted on aircraft. This radome is made of glass fibre to make sure the digital signals from the radar can penetrate the material unimpeded. When the radome also houses instruments that are crucial for controlling the aircraft, it is extremely important that this part of the aircraft is protected from lightning strikes. The diverter strips used in aviation need to be modified for use in protecting wind turbine blades, as they are designed to be replaced after just one or two lightning strikes.

It has therefore been necessary to develop completely new principles when developing diverter strips for wind turbine blades.

## Description of LM DiverterStrip

There is a general distinction between two types of diverters – solid and segmented.

Solid diverters [4] are continuous metal bars placed on the surface to intercept a lightning strike and conduct the current to an adjacent metallic structure. These diverters are designed to conduct the lightning current – typically of a magnitude of 200 kA – away from the zone where the part is located, thus avoiding damage. Solid diverters are usually made of aluminium with a rectangular cross section sufficient to enable conduction of the current without an excessive increase in temperature. For mechanical reasons and to prevent holes for fasteners from reducing the cross-sectional area unduly, most diverters have additions to the cross-sectional area.

If solid diverters are installed on the outer surface, they may cause some drag, especially if placed perpendicular to the air flow.

Segmented diverters [4] consist of a series of thin, conductive segments, sometimes interconnected by a resistant material and fastened to a thin composite strip that can be cemented to the surface to be protected (see figure 6).

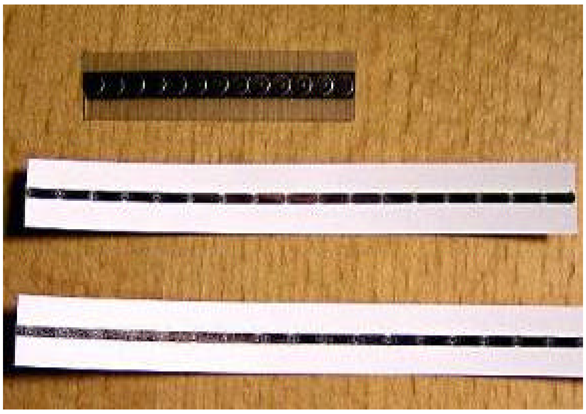


**Figure 6:** Top "button" segmented diverter with resistant material, used mostly on aircraft with an analogue radar antenna signal. Middle and bottom segmented diverter mostly used on newer aircraft with a digital antenna signal.

Segmented diverters do not provide a metal path to conduct the lightning current. Instead, they provide many small air gaps that ionise when a high electric field is applied. Because these gaps are close together, the resulting ionisation is virtually continuous and thus provides a conductive path of lightning leaders and flash current. These segmented diverters thus guide, rather than actually conduct, the flash across the protected surface.

For the segmented diverter to ionise, there must be an electrical field tangential to the length of the diverter. This is provided by the approaching lightning leader.

The maximum spacing between the segments in the diverter, and the minimum permissible spacing to underlying conductors (carbon laminate), depends on the voltage required to ionise the segmented strips. Ideally, the ionisation voltage is lower than that required to ionise a path along the bare surface of the blade. It is also much lower than that required to puncture through the glass fibre insulation into the carbon laminate. Laboratory tests conducted on LM DiverterStrips have shown an ionisation level of 20–50 kV per metre, which corresponds to the level of commercially available diverter strips. This is much less than the 500–700 kV per metre required to ionise the air across an insulated surface, such as a glass fibre blade.

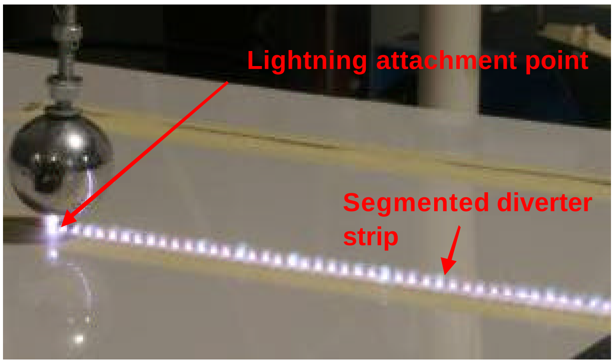



**Figure 7:** Shows the ionisation between each segment on a prototype LM Glasfiber diverter.

Advantages of LM DiverterStrip:

- Specially developed for use on rotor blades.
- Low maintenance. Designed to last for 20 years.
- Low weight.
- Easy to mount on the blade. Require no drilling holes.
- Can be retrofitted.
- Minimal influence on the air flow over the blade, compared with solid diverters.
- No current flow in segmented diverters compared with solid diverters. This means no electromagnetic effects.
- Current travelling in an ionised path above the segments of the LM DiverterStrip makes a smooth transfer to the receptor.
- LM DiverterStrip withstands more lightning impacts compared with commercially available segmented diverters, due to their robust design.
- The corrosion properties of LM DiverterStrip are better than commercially available segmented diverters due to the choice of materials and processing.

Disadvantages of LM DiverterStrip:

- Ionisation does not take place if covered with a thick layer of ice.
- Streamer and leader propagation is slightly slower with segmented diverter strips than with solid diverters, because ionisation adds an additional phase to the lightning event.
- Surface-mounted diverter strips influence the noise level and the aerodynamic performance, but not to a critical level.

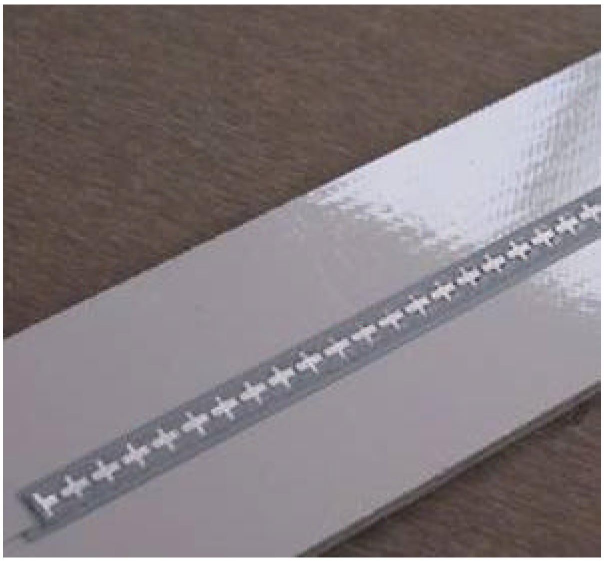


**Figure 8:** The final LM DiverterStrip mounted on a piece of laminate.

## Verification

Many different types of segmented diverters were tested at the beginning of the development stage. These included commercially available diverters as well as those developed by LM Glasfiber. Several different materials were also tested at this time. These tests were carried out using lightning impulse voltage testing on a blade segment.

The ionisation voltages for each diverter are an indication of how effective the protection they provide actually is, because diverters that ionise at the lowest voltages provide the best protection against puncture through alternate paths. The ionisation voltages of different diverters were determined by applying a lightning impulse voltage with a virtual peak of 255 kV. This was higher than the expected ionisation voltages, so that the test voltage increase was interrupted by ionisation of the diverter. This made it possible to record the voltage at which ionisation took place.

For the ionisation voltage tests, 50 cm lengths of the diverter candidates were taped temporarily to the gelcoat surface adjacent to a receptor, in a manner similar to the intended diverter application on the LM 61.5 P blade. The test voltage was applied from a small sphere positioned 5–10 cm from one end of the diverter being tested. The other end of the diverter was adjacent to the receptor (see figures 9, 10 and 11).

**Figure 9:** First tests with a commercially available thin copper wire diverter in a sine wave shape and disconnected at the peak of each wave period. The receptor can be seen at the bottom end of the diverter.

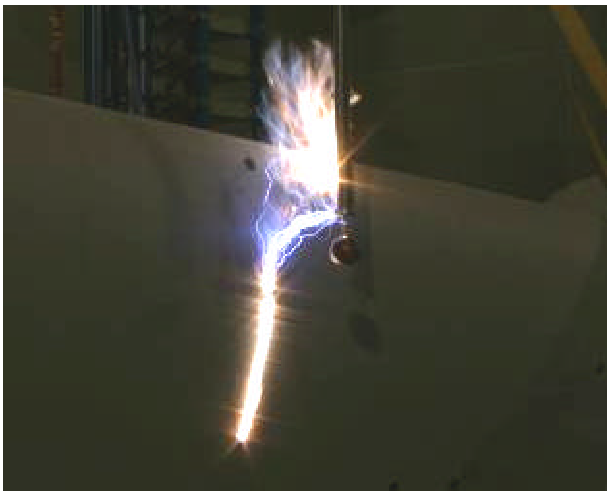


**Figure 10:** The copper wire diverter from figure 9 during the lightning impulse test with a copper sphere. Some lift-off (ionisation) can be seen, as indicated by the colour of the flashover. The ideal flashover is entirely white with no shades of blue or red.

**Figure 11:** The cobber wire diverter after the Lightning Impulse test seen in figure 10. Numerous burns are visible around each sine-shaped piece of wire.

A similar arrangement was used to evaluate arc lift-off capabilities of the diverters being tested. Arc lift-off is necessary to prevent damage to the conductive segments in the diverter. Lift-off is known to commence within several microseconds of initial ionisation. For lift-off to be confirmed, the electric arc must exist for sufficient time to move away from the surface of the diverter and be photographed, as in figure 7.

A number of high-voltage tests were carried out on blade specimens and test laminates before the development of the final LM DiverterStrip. Part of the design phase involved determining the level of electrical insulation needed beneath the diverter in order to avoid puncturing the conductive materials in the blade, such as carbon laminate.

LM DiverterStrip underwent high-current (HC) testing to see if the increases in pressure and temperature stemming from the lightning would harm the diverter. The LM DiverterStrip performed very well and remained unharmed, as seen in figure 12.

**Figure 12:** LM DiverterStrip following test at 248 kA, 3.2MJ/ohm.

In addition to the High Voltage and High Current tests LM DiverterStrips were tested in climate chamber to ensure that they will withstand the UV light from the sun as well as different humidity and temperature scenarios.

During the last stage of development, the LM DiverterStrip was tested on carbon fibre blades, and the results were convincing.

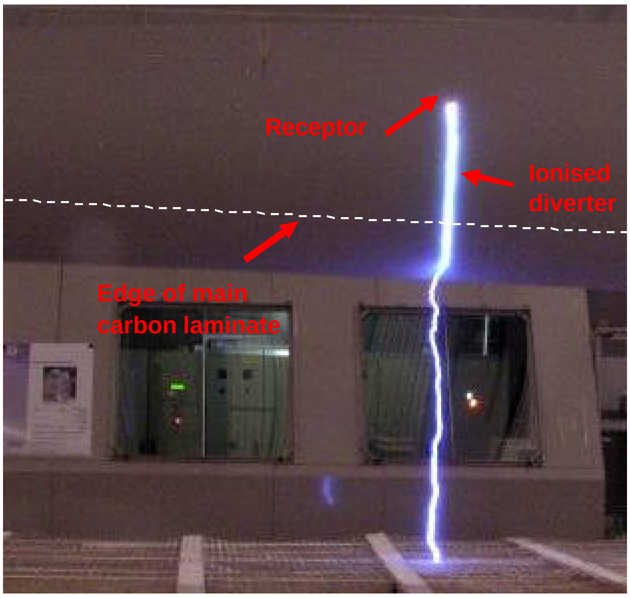



**Figure 13**: High Voltage impact test performed with LM DiverterStrip. The flashover very clearly occurs to the diverter and not to the leading edge of the main carbon laminate as is the case in figure 14.

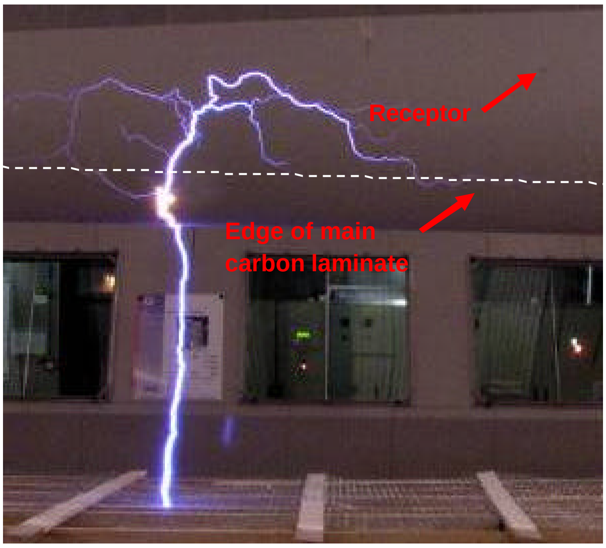



**Figure 14:** High-voltage impact test. The leading edge of the main carbon laminate is more likely to attract the lightning current than the receptor seen in the upper right corner – no diverters mounted.

The high voltage impact test without diverters showed punctures to the carbon fibres in the laminate, see figure 14. The similar test with LM DiverterStrips provided perfect guidance of the flashover to the receptor and no damage (punctures) to the blade, see figure 13.

## Conclusion

LM DiverterStrip provides LM Glasfiber carbon fibre wind turbine blades with effective protection against damage from lightning strikes. The height of the wind turbines contributes to boosting the frequency of lightning strikes on the blades, and this frequency varies according to the location.

**Figure 17:** LM DiverterStrip mounted on the prototype LM 61.5 P blade on the 5 MW Repower Systems wind turbine. Photo taken after nearly one year of operation.

The low-maintenance solution for intercepting lightning on the actual surface of the blades makes unnecessary inspections and repairs a thing of the past. This has particular significance for the profitability of offshore wind farms.

LM DiverterStrip is specially developed to last the entire 20-year service life of the wind turbine. This is due to both the robust materials used and the way they are attached securely on to the blade. Numerous laboratory tests were performed to verify this, both in high voltage and high current situations.

*LM Glasfiber has applied for international patents for this new principle.*

## Bibliography


[1] Lightning Diversion Systems

Aircraft Lightning Diversion Strips
www.Lightningdiversion.com

[2] Paper from Cired 2001 conference

Lightning protection for offshore wind turbines.

Amsterdam, The Netherlands 18-21 June 2001

[3] Glen Salo and Edward J. Rupke.

RSPHERE, a numerical code for predicting lightning attachment based on the rolling sphere concept. ICOLSE 2005 (IO3-52 CEM), Blackpool

[4] F.A. Fisher, R.A. Perala and J.A. Plumer

Lightning Protection of Aircraft, second printing 1999. Published by Lightning Technologies, Inc.